

Arrival Flight Efficiency in Numbers: What New the Covid-19 Crisis is Bringing to the Picture?

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Abstract—Covid-19 pandemic affected aviation severely, resulting in unprecedented reduction of air traffic. While aviation is slowly re-gaining traffic volumes, we use the opportunity to study the arrival performance in the Terminal Maneuvering Area (TMA) in non-congested scenarios.

Applying flight efficiency and environmental performance indicators (PIs) to the historical data of arrivals to Stockholm Arlanda airport, we discover noticeable inefficiencies, despite significant reduction of traffic intensity. We analyse the impact of such factors as weather and traffic intensity on arrival efficiency in isolated scenarios when only one factor dominates. Our analysis uncovers that weather has a stronger influence than congestion on vertical efficiency, while congestion affects both, but mostly lateral efficiency.

Keywords—Vertical Flight Efficiency; Continuous Descent Operations; Fuel Consumption; Key Performance Indicators; Weather Impact on Flight Efficiency; Covid-19

I. INTRODUCTION

The Covid-19 pandemic has had a significant impact on the aviation industry due to travel restrictions and resulted in unprecedented reduction in air traffic worldwide (for Europe up to 88.2% in April [1] and 85.9% in May [2]). Massively reduced revenues forced many airlines to lay off employees or declare bankruptcy. All aviation stakeholders got affected by the pandemic.

Apart from the negative effects of the pandemic, there are also some positive trends. According to [3] daily global CO_2 emissions decreased by 17% by early April 2020 compared with the mean 2019 levels. At their deepest point, emissions in individual countries decreased by 26% on average.

As outlined in one of the SESAR JU Digital Sky vodcasts [4], during the pandemic time aviation community should be able to benefit from the unique opportunity to test the new operational concepts and initiatives in real non-congested scenarios. In this work, we compare operations in spring-summer 2020 against the same period in 2019, and perform a comprehensive analysis for these two periods. We apply the methodology developed in [5], enhanced with two additional

This research is a part of the IFWHEN project supported by the Swedish Transport Agency (Transportstyrelsen), and TMAKPI project supported by the Swedish Transport Administration (Trafikverket). It is also supported by the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 783287.

impact factors: Weather Impact Factor (WIF) and Traffic Impact Factor (TIF). We study which of the factors has a stronger influence on which aspects of the arrival flight performance, in isolated scenarios with only one of the factors present.

The rest of the paper is organized as follows. In Section II we present state of the art, in Section III we describe the PIs and the methodology we propose for investigation of the impact factors influencing arrival performance. Section IV presents the results of the experimental evaluation, and Section V concludes the paper and outlines future work directions.

II. RELATED WORK

Flight Efficiency. Evaluation of flight efficiency, and in particular TMA performance, has been a topic of interest in recent years. International Civil Aviation Organization (ICAO) proposed a set of Key Performance Indicators (KPIs) to enable analysis of TMA performance [6].

EUROCONTROL developed the methodology used by its Performance Review Unit (PRU) for the analysis of vertical flight efficiency (VFE) during climb and descent [7]. Performance Review Commission of EUROCONTROL made an assessment of ATM in Europe for the year 2019, where among other indicators reviewed flight inefficiency within TMA at the top 30 European airports, including Stockholm Arlanda airport [8].

Pasutto et al. [9] analyze the factors affecting vertical efficiency in descent at the top 30 European airports. The paper reveals an increase of the vertical deviation with the horizontal deviation, and a dispersion of the vertical deviation for the same horizontal deviation. The analysis also reports a very significant disparity among airports, with some indicators ranging by a factor of 5 or more. Zanin [10] evaluates the efficiency of flights landing at an airport using open large-scale data sets of aircraft trajectories. The author focuses on understanding the efficiency of different airspaces and on comparing them.

Estimation of the flight inefficiencies in terms of extra fuel burn calculated based on the algorithm proposed in [11] was considered in the scope of APACHE project (a SESAR 2020 exploratory research project) [12], [13], but mostly for en-



route flight phase. Later Prats et al. [14] proposed a family of performance indicators to measure fuel inefficiencies.

In [15] fuel consumption is evaluated for terminal areas with a Terminal Inefficiency metric based on the variation in terminal area fuel consumed across flights, reported by a major U.S. airline. Using this metric they quantify the additional fuel burn caused by ATM delay and terminal inefficiencies. Furthermore, in [16] and [17], fuel savings of the Continuous Descent Operations (CDOs) with respect to conventional procedures are analyzed. A reduction in fuel consumption of around 25-40% by flying CDOs was reported.

Weather Impact. Quantification of the impact of different weather phenomena on airport operation is reflected in many recent research activities. Schults et al. [18] used the ATMAP algorithm, published by Eurocontrol's Performance Review Unit (PRU), which transforms the METAR data into the aggregated weather score weighting the different weather factors. They analysed the correlation of the on-time performance of flight operations with the ATMAP score at major European airports.

Impact of deep convection and thunderstorms is also subject to ongoing research, e.g. Steiner et al. [19], [20] and Song et al. [21] investigated their implication both on the en-route flow management and on terminal area operations. Klein et al. [22] used a high-level airport model to quantify the impact of weather forecast uncertainty on delay costs. Steiner et al. [23] discuss the crucial effect of accurate forecasts of high-impact winter weather for efficient management of airport and airline capacity and highlight the need of data sharing and integrated decision making between stakeholders. Recent works [24], [25] confirmed the relevance and emphasized the importance of quantification and analysis of the weather impact on airport operation.

In [5], [26], [27] Lemetti et al. presented a detailed assessment of Stockholm Arlanda arrival performance, as well as investigated the impact of different factors influencing the efficiency of arrivals. High traffic volume was assumed in most of the considered scenarios, as the analysis was based on the historical flight data from the year 2018. In this paper we are focusing on low traffic scenario and an isolated scenario of good weather conditions.

III. METHODOLOGY

In this section we present the performance indicators we use for comparative analysis of arrival efficiency in pre-pandemic and after-pandemic conditions. We also list the impact factors we consider for investigation of the reasons for performance inefficiencies in TMA. In addition, we describe the methodology used for estimating the CDO speed profiles for the arrival flights.

A. Performance Indicators

To evaluate TMA performance we use the following performance indicators (PIs): Time Flown Level, Time in TMA and Additional Fuel Burn.

1) *Average/Median Time Flown Level:* Vertical inefficiencies during the descent phase result from the inability of flights to follow CDOs. CDOs enable the execution of a flight profile optimized to the operating capability of the aircraft, resulting in optimal continuous engine-idle descents (without using speed-breaks). If the aircraft levels at intermediate altitudes before landing, the descent is considered to be vertically inefficient. Average Time Flown level is the KPI proposed by ICAO (*KPI19.2* [6]) to evaluate vertical flight inefficiency.

For calculating Time Flown Level inside TMA, we use the techniques proposed by EUROCONTROL in [7] with small changes. We identify the point of the trajectory in which the aircraft enters the TMA and use it as a starting point for the calculations (instead of the Top of Descent (ToD), which may lie outside of TMA). A level segment is detected when the aircraft is flying with the vertical speed below the certain threshold. We use the value of 300 feet per minute for this threshold, the minimum time duration of the level flight is considered 30 seconds, and these 30 seconds are subtracted from each level duration as suggested in [7]. We do not consider as level the flight under 1000 feet, corresponding to the final approach.

2) *Average/Median Time in TMA:* Time in TMA is the actual transit time the aircraft spends in TMA. To calculate the exact time we use the data of high granularity and determine the exact second the aircraft enters the terminal area. As the last timestamp we take the moment the aircraft reaches the final approach.

3) *Additional Fuel Burn:* Fuel-based PIs capture inefficiencies on tactical ATM layer in vertical domain as explained in [14]. The objective is to generate a set of CDO trajectories, calculate the fuel consumption for those, and compare against the calculated fuel consumption of the actual trajectories.

B. Impact Factors

In this work, we examine the influence of several impact factors, such as traffic intensity and different weather conditions on the arrival flight performance within TMA. To quantify the impact of weather, we consider the following weather metrics: wind gust, cloud base height, low cloud cover and convective available potential energy (CAPE). Snow is not taken into consideration as the probability of snowy weather is quite low during the spring-summer season.

1) *Traffic Intensity:* We analyze flight efficiency during the descent and consider the number of arriving aircraft. Normalized number of arrivals per hour was used as a traffic intensity.

2) *Wind Gust:* Difficult wind conditions can influence the ability of the aircraft to keep up CDOs. Wind gust is a brief increase in the speed of the wind, measured in $m \times s^{-1}$. Our investigation shows that wind gust has bigger influence on flight efficiency than wind speed calculated from zonal and meridional wind components, thus we use this metric.

3) *Low Cloud Cover:* Cloud cover is the fraction of the sky covered by all the visible clouds. The usual unit of measurement of the cloud cover is *okta*, which is a number



of eighths of the sky covered in cloud. Low cloud cover is the proportion of clouds occurring in the low levels of the troposphere.

4) *Cloud base height*: Cloud base height is the height above the Earth's surface of the base of the lowest cloud layer, measured in *meters*. Depending on cloud ceiling and runway visual range the spacing of aircraft on final approach must be increased. Ceilings and cloud cover impact both visual (VFR) and instrument flight rules (IFR). Cloud based height together with low cloud cover are used to assess visibility [28].

5) *Convective Available Potential Energy (CAPE)*: CAPE is the energy a parcel of air has for upward motion, measured in joules per kilogram of air ($J \times kg^{-1}$). It indicates atmosphere instability and a possibility of thunderstorms and severe straight line winds.

6) *Aggregated Impact Factor*: Aggregated impact factor (AIF) is a unified condition metric, representing the current weather and traffic situation. The methodology of AIF calculation is detailed in [5]. In this work, we take other weather metrics to contribute to AIF: wind gust, cloud base height, low cloud cover and CAPE. AIF values are calculated per hour. Summing up normalized metrics we substitute cloud base height (*cbh*) term by $1 - cbh$.

7) *Weather Impact Factor*: Covid-19 gives us an opportunity to investigate an isolated scenario of low traffic flight performance. Assuming traffic intensity does not influence the flight efficiency in this scenario (there are 0-3 arrival flights per hour at Arlanda), we create a unified weather condition metric and call it Weather Impact Factor. We apply the same methodology as for AIF calculation, but taking only weather metrics as contributing factors.

8) *Traffic Impact Factor*: We investigate an isolated scenario of flight performance in good weather conditions. Assuming the isolated scenario with no influence of weather, we take into account only traffic intensity and calculate Traffic Impact Factor (TIF) by discretizing the traffic intensity into 10 bins.

C. Generation of the CDO Profiles

We calculate the CDO trajectories for all aircraft arrivals to TMA, using the given entry conditions, with the goal to use them as a reference for calculation of the fuel-related PIs. For that we use the predefined speed profiles as follows. We use the speed profiles for jet aircraft (Table I) and for turboprop aircraft (Table II), developed based on aircraft data and the information from SKYbrary [29]. The general idea is to let the aircraft initially descend at a constant Mach number, while the calibrated airspeed (V_{CAS}) is increasing, until reaching a $V_{CAS,transition}$ speed, where a constant V_{CAS} is maintained. We set a speed limit of $V_{CAS,max} = 250$ kt below FL100, which is a typical speed limit inside TMA. We also use further speed reductions at lower altitudes and set the length of the CDOs equal to the actual distance flown in TMA for the studied flights.

We use the Base of Aircraft DATA (BADA) version 4.1 [30] to model the descent of the aircraft at idle thrust. We assume

TABLE I. DESCENT SPEED PROFILE FOR JET AIRCRAFT.

Segment	Break condition	Speed
1	$V_{CAS} = 290$ kt	$M = 0.78$
2	Alt = FL100	$V_{CAS} = 290$ kt
3	Alt = FL60	$V_{CAS} = 250$ kt
4	Alt = 4000 ft	$V_{CAS} = 210$ kt
5	-	$V_{CAS} = 160$ kt

TABLE II. DESCENT SPEED PROFILE FOR TURBOPROP AIRCRAFT.

Segment	Break condition	Speed
1	$V_{CAS} = 230$ kt	$M = 0.50$
2	Alt = FL70	$V_{CAS} = 230$ kt
3	Alt = FL55	$V_{CAS} = 200$ kt
4	Alt = 4000 ft	$V_{CAS} = 160$ kt
5	-	$V_{CAS} = 120$ kt

International Standard Atmosphere (ISA) conditions for all CDOs, and hence, we exclude from the formulas the effects caused by non-ISA temperatures. We set the reference mass to 90% of the aircraft max landing weight defined in BADA.

From the Total Energy Model (TEM), we derive the rate of descent and initialize the calculations by setting a starting altitude at $t = t_0$. Then we calculate the rate of descent achieved by keeping idle thrust at the current speed, which yields a new altitude at $t = t_1$. This loop is continued until the aircraft reaches a predefined final altitude. By calculating the rate of descent at every time step, we obtain the vertical trajectory of the CDOs.

D. Fuel Consumption

To estimate the fuel consumption for the CDOs, we calculate the idle fuel coefficient, C_F , based on formulas from BADA, and input it to the the equation for fuel flow:

$$F = \delta \cdot \theta^{\frac{1}{2}} \cdot m \cdot g_0 \cdot a_0 \cdot L_{HV}^{-1} \cdot C_F \quad (1)$$

Here, δ is the pressure ratio, θ is the temperature ratio, m is the reference mass, g_0 is the gravitational acceleration, a_0 is the speed of sound at sea level and L_{HV}^{-1} is the fuel lower heating value.

For the actual trajectories, we use the TEM as a reference for calculating the thrust, obtaining the temperature and wind conditions at different pressure altitudes from historical weather data (see section IV-A). Then we use the thrust to obtain the thrust coefficient. To ensure the calculated thrust stays within the feasible limits, we use BADA formulas for calculating the thrust at the maximum climb rating and idle rating, which bound the calculated thrust from below and above.

Next, we calculate the fuel coefficient from the thrust coefficient, and then input to the formula for the fuel flow calculation in Equation 1. We do not take into account the effects of deploying flaps at lower speeds, which will generate more drag and increase the fuel consumption.

IV. EXPERIMENTAL EVALUATION

This section describes the data used in this work and presents the results of the data analysis we perform to study the

impact of traffic intensity and weather on arrival performance at Stockholm Arlanda airport. We investigate the period of five months from March to July of the years 2020 and 2019 to compare flight efficiency in high and low traffic conditions.

A. Data

In this work we use multiple sources of historical data related to the performance of Stockholm Arlanda during the months March-July of the years 2019 and 2020.

1) *Aircraft tracking information:* For the historical flight trajectories we use the Historical Database of the OpenSky Network [31], [32]. We use aircraft state vectors for every second of the trajectories inside TMA. Noncommercial flights, such as ambulance, police helicopters and Swedish Armed Forces air transport flights are removed from the downloaded dataset using specificity of their callsigns.

Flightradar24 [33] is a Swedish Internet-based service that shows real-time commercial aircraft flight tracking information on a map. We use this data source for some additional investigation of flight inefficiency during the specific days.

2) *Aircraft performance data:* We use BADA version 4.1 [30] for CDO trajectory generation and fuel consumption calculation. For aircraft types operated by the studied flights not available in BADA, we replace it by a type similar in performance and size.

3) *Weather data:* The source of historical weather data in this paper is ECMWF [34] ERA5 reanalysis dataset provided via the C3S Data Store in form of NetCDF files with 0.25° granularity and temporal granularity of one hour. The data is used for evaluation of weather impact on flight efficiency as well as for fuel consumption calculation.

Airports record current weather conditions in the form of Meteorological Aerodrome Reports (METARs). Historical METARs data is accessible at different publicly available web sources, e.g. [35] We use METARs data to get more precise information about the weather on the specific days.

B. PIs Calculation

In this subsection, we detail how we calculate the performance indicators, which we use to assess arrival efficiency.

1) *Time Flown Level, Time in TMA:* To calculate Time Flown Level and Time in TMA we use OpenSky states data. High granularity of OpenSky states data allows to determine the exact seconds the aircraft enters the terminal area and reaches the final approach. The database also provides very accurate levels in aircraft descent. To study Covid-19 impact on flight performance we calculate average Time in TMA and average Time Flown Level per day for the months March-July of the years 2019 and 2020. To reveal the possible correlations between the PIs and impact factors we take median per hour values for the same period.

2) *Additional Fuel Burn:* We evaluate the fuel efficiency for two chosen days of the year 2020. To calculate actual fuel consumption we use the trajectories from OpenSky Network states data. Since Opensky data is very dense, we sparsify the selected dataset by using every third recording, which

reflects aircraft position every three seconds and results in less fluctuations. We also filter out erroneous position records, as well as false altitude records. After the true airspeed and the rate of descent are calculated, we apply a smoothing technique to further reduce the amount of sudden fluctuations. For CDOs calculation the distance to go is also obtained from the Opensky Network data, using state vectors for every second of the corresponding flight within TMA.

C. Analysis of the Influence of Traffic Intensity on TMA Performance

Figure 1(a) illustrates that air traffic dramatically decreased in April 2020, comparing to March 2020 and to all months under consideration in the year 2019. To examine whether this recession resulted in increased flight efficiency, we plot the PIs by days for the considered time period (see Figures 1(b), 1(c)) and regress the PIs onto the number of flights. The regression shows a weak correlation between the Average Time Flown Level and the traffic intensity ($R^2 = 0.11$). For Average Time in TMA the correlation is moderate ($R^2 = 0.43$). Figure 1(b) confirms that the arrival performance in 2020 has slightly increased in terms of time spent in TMA in comparison to the previous year. VFE PI does not indicate any improvements (see Figure 1(c)).

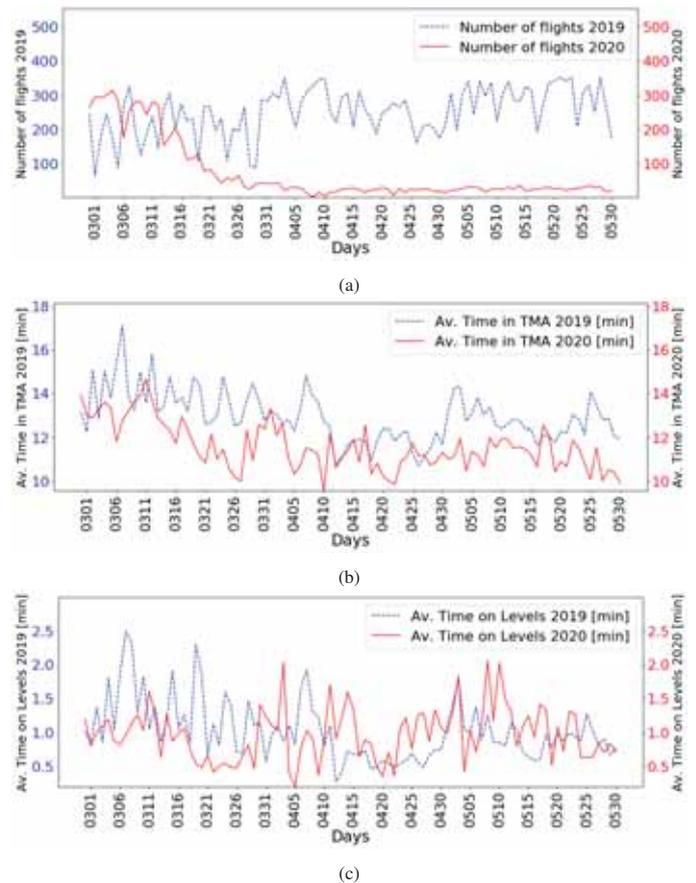


Figure 1. Number of arrival flights (a), Average Time in TMA (b) and Average Time Flown Level (c) at Stockholm Arlanda airport for the months of March, April and May in the years 2019 and 2020.

D. Analysis of the Influence of Weather and Traffic Intensity on TMA Performance

To analyse the influence of weather conditions together with the traffic situation on our PIs inside TMA, we apply methodology developed in [5]. Using the data for the months March-July of the years 2019 and 2020, we perform the regression of the Time in TMA and Time Flown Level medians onto AIF values and get the strong correlation between the PIs medians and the AIF, with $R^2 = 0.94$ for Time in TMA, and $R^2 = 0.96$ for Time Flown Level (illustrated in Figures 2(a), 2(b)). This result proves that the chosen weather factors as well as traffic intensity have a noticeable impact on the chosen PIs when applied simultaneously.

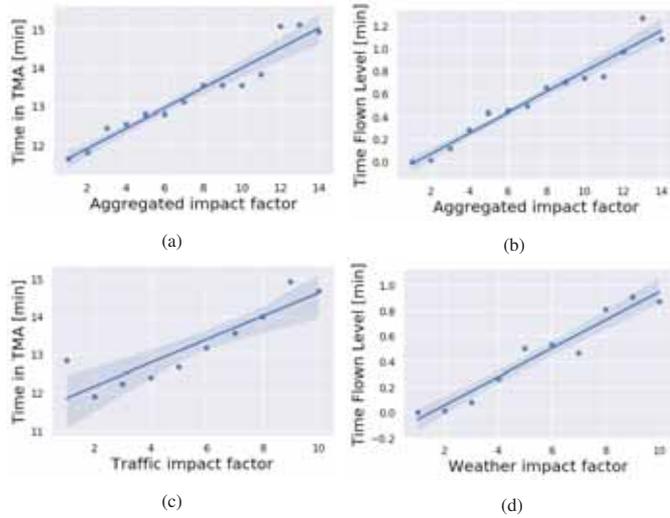


Figure 2. Regression of Time in TMA median values onto the AIF ($R^2 = 0.94$) (a), Time Flown Level median values onto the AIF ($R^2 = 0.96$) (b), Time in TMA median values onto the TIF ($R^2 = 0.81$) (c) and Time Flown Level median values onto the WIF ($R^2 = 0.94$) (d).

E. Analysis of Flight Efficiency within TMA in an Isolated Scenario with Low Traffic

To analyze the weather impact and to determine which PI is more affected by weather, we reduced our time interval to April-July for the year 2020. We apply the same technique as we used for AIF but exclude the traffic intensity, getting as a result an aggregated Weather Impact Factor (WIF). Regressing the medians of our PIs onto WIF values we notice significantly stronger correlation ($R^2 = 0.94$) for vertical efficiency (see Figures 2(d)). Time in TMA shows moderate correlation with WIF ($R^2 = 0.62$).

F. Analysis of Flight Efficiency within TMA in an Isolated Scenario with Good Weather Conditions

Considering that Time in TMA correlates with AIF, we assume that the most significant factor that influences this PI is traffic intensity (Figure 1(b) reinforce this assumption). We investigate an isolated scenario with good weather conditions. Taking our full time period of 10 months of the years 2019 and 2020, we exclude from the consideration all the days,

when weather metrics violate at least one of the following thresholds: wind gust ≤ 25 knots, cloud base height ≥ 200 feet, low cloud cover < 1 , CAPE ≤ 150 J/kg. We use the work by Taszarek et al. [28], who defined these threshold values for the definition of the hazardous types of different weather phenomena. Regression of Time in TMA medians onto TIF confirms that traffic intensity significantly influences this PI ($R^2 = 0.81$ see Figure 2(c)). Regression of Time Flown Level medians expectedly shows weaker correlation ($R^2 = 0.47$).

G. Fine-grained Analysis of Flight Inefficiency within TMA in Low Traffic Conditions

1) *Vertical Efficiency*: To examine the vertical efficiency further, we choose two days with high values of the Average Time Flown Level PI: April 12 and May 4 of the year 2020. Figures 3(a), 3(b) show the actual vertical profiles and their corresponding estimated CDO profiles for the chosen days. We observe that the aircraft start to descend earlier and fly significantly lower and often longer than recommended by CDO trajectories. Some of them have long levels at the low altitudes.

Next, applying the methodology similar to the one proposed in [9], we differentiate between the inefficiencies in lower and upper parts of the TMA. For that we split the trajectories as shown in Figures 3(c), 3(d) with the different colored parts representing inefficiencies below and over the FL65. Calculating average deviation for lower and upper parts of the trajectories, we observe higher deviations from the CDOs in the upper parts of the flights with median value of 1103 m on April 12 and 1099 m on May 4. For the altitudes below FL65 the median values are 559 m and 492 m correspondingly.

2) *Additional Fuel Burn*: The results of comparison of the fuel consumption for the actual aircraft trajectories against the fuel consumption estimated for the CDO profiles, show that there are noticeable inefficiencies, despite the low traffic volume (Figure 4 and Figure 5). For April 12, the estimated additional fuel burn is 1416 kgs (42%), and for May 5 – 1444 kgs (41%). However, we observe that some of the actual trajectories burn slightly less fuel than the CDOs, which might be explained either by the dataset errors, or by a non-optimal CDO trajectory prediction technique.

Very high values of the fuel consumption for the aircraft 4 and 5 in Figure 5, could possibly be explained by weather influence. According to historical METARs from OGIMET [35], cumulonimbus (CB) clouds were present in the area of Arlanda TMA, at the time of arrival of the two flights. By performing a playback of the flights around Arlanda TMA at FlightRadar24 website [33], we can see that all arriving flights on May 4, 2020, landed on runway 01L, while aircraft 4 and 5 landed on runway 26 (Figure 6). Following the flight paths of the two flights, we can guess that the two flights initially were heading towards runway 01L, but were diverted to runway 26 because of the bad weather conditions, i.e. CB clouds present in the final approach path to runway 01L. The diversion is clearly visible for SAS88R, while SAS58E is flying a right-hand circuit, instead of approaching the final from the south,

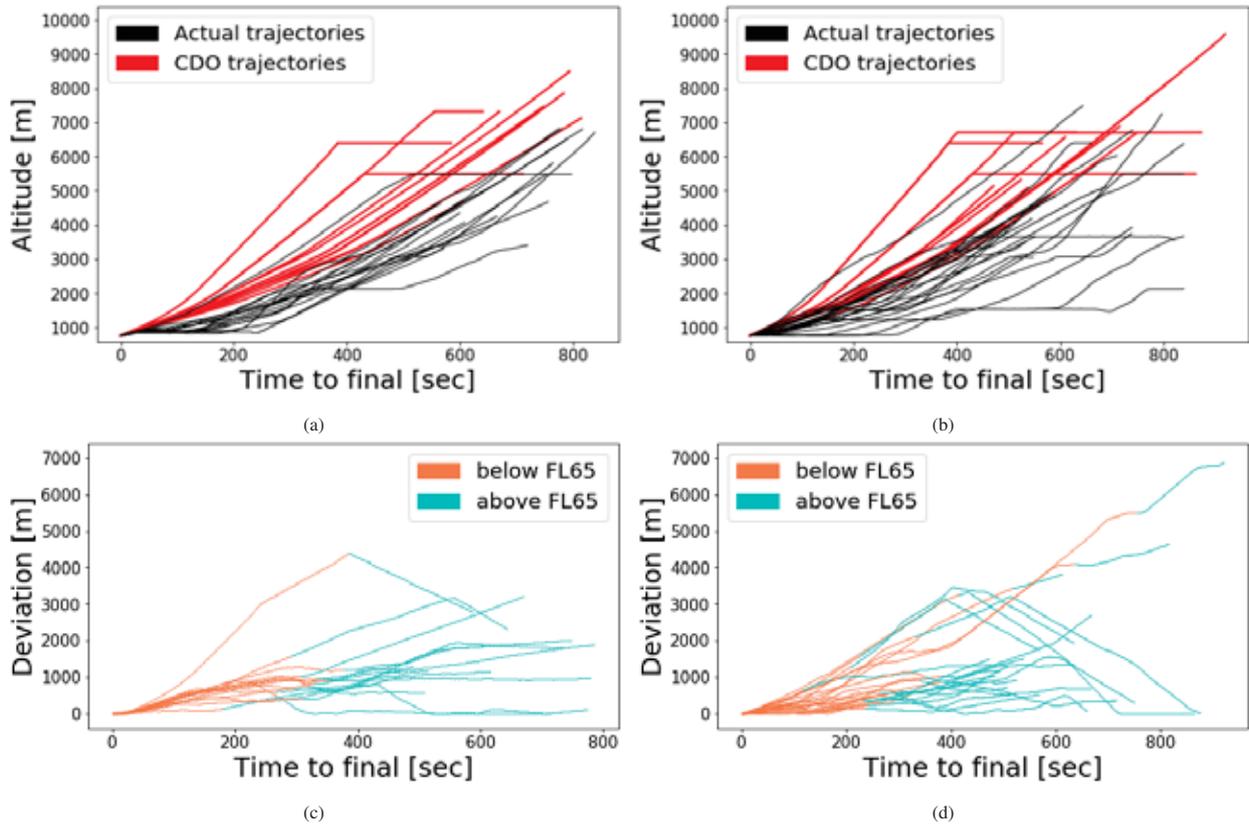


Figure 3. Vertical profiles of the arrival flights in Stockholm Arlanda airport TMA together with CDOs on April 12 (a) and May 4 (b), 2020. Vertical deviations from CDOs on April 12 (c) and May 4 (d) of the year 2020.

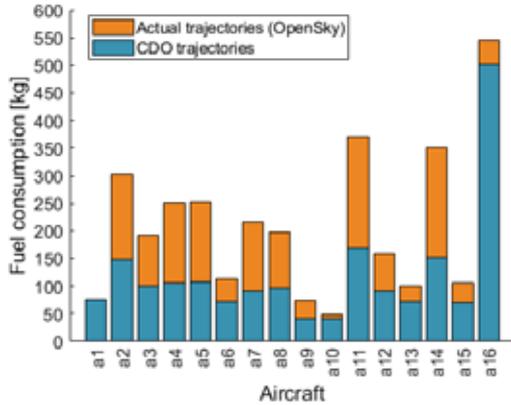


Figure 4. Comparison of the fuel consumption for the actual aircraft trajectories against the CDOs, for 16 arrivals within Arlanda TMA on April 12, 2020.

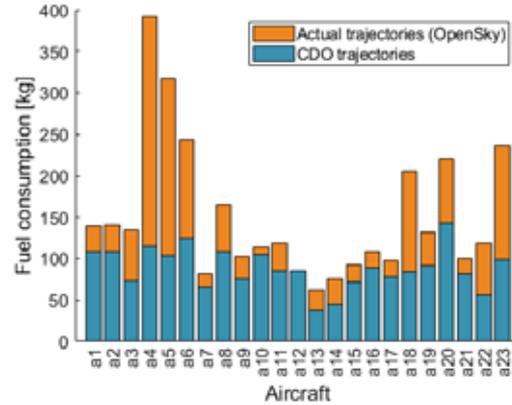


Figure 5. Comparison of the fuel consumption for the actual aircraft trajectories against the CDOs, for 23 arrivals within Arlanda TMA on May 4, 2020.

which is the typical way of approaching runway 26 coming from the southern parts of the TMA, and we can suppose that the aircraft was deliberately diverted out of the certain parts of the TMA by the air traffic controller.

V. CONCLUSIONS AND FUTURE WORK

In this work, we used the opportunity provided by the Covid-19 pandemic situation to evaluate TMA performance

in an isolated scenario with low traffic in Stockholm Arlanda airport. We revealed that the time spent by aircraft in TMA has decreased compared to the pre-pandemic scenario. At the same time, vertical flight efficiency has not improved despite the low traffic volumes. In particular, we discovered noticeable vertical inefficiencies on two days in 2020 (in low-traffic scenario), and evaluated the associated environmental effect, which corresponds to up to 42% extra fuel burned.

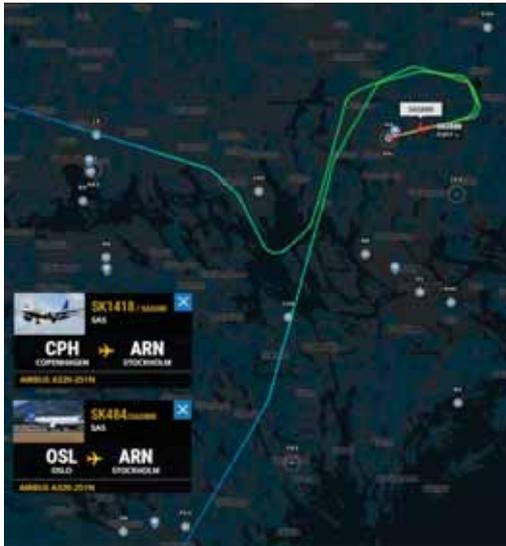


Figure 6. Aircraft trajectories for the flights SAS88R and SAS58E on May 4, 2020.

We confirmed that weather conditions have a significant impact on vertical flight efficiency. We also evaluated an isolated scenario with good weather conditions and concluded that traffic intensity has a strong impact on TMA performance but influences mostly the lateral efficiency.

The results of this work contribute to the understanding of sources of flight inefficiency within TMA. We target integration of the advanced weather prediction methodologies, developed within the related SESAR projects (e.g. [36], [37]), into the evaluation and subsequent optimization of routing within TMA.

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